

Investigating the effect of using three pozzolans (including the nanoadditive) in combination on the formation and development of cracks in concretes using non-contact measurement method

Grzegorz Ludwik Golewski*

Department of Structural Engineering, Faculty of Civil Engineering and Architecture, Lublin University of Technology,
Nadbystrzycka 40 str., 20-618, Lublin, Poland

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Abstract. This paper presents results of visual analysis of cracks formation and propagation of concretes made of quaternary binders (QBC). A composition of the two most commonly used mineral additives, i.e. fly ash (FA) and silica fume (SF) in combination with nanosilica (nS), has been proposed as a partial replacement of the cement. The principal objective of the present study is to achieve information about the effect of simultaneous incorporation of three pozzolans as partial replacement to the OPC on the fracture processes in concretes made from quaternary binders (QBC). The modern and precise non-contact measurement method (NCMM) via digital image correlation (DIC) technique was used, during the studies. In the course of experiments it was established that the substitution of OPC with three pozzolans including the nanoadditive in FA+SF+nS combination causes a clear change of brittleness and behavior during fractures in QBCs. It was found that the shape of cracks in unmodified concrete was quasi-linear. Substitution of the binder by SCMs resulted in a slight heterogeneity of the structure of the QBC, including only SF and nS, and clear heterogeneity for concretes with the FA additive. In addition, as content of FA rises throughout each of QBC series, material becomes more ductile and shows less brittle failure. It means that an increase in the FA content in the concrete mix causes a significant change in fracture process in this composite in comparison to concrete with the addition of silica modifiers only.

Keywords: cracking; fly ash (FA); nanosilica (nS); non-contact measurement method (NCMM); ordinary Portland cement (OPC); quaternary binder concrete (QBC); silica fume (SF); visual analysis

1. Introduction

When looking at the production process of concrete, which is the currently basic construction material, it should be realized that its production – despite the fact that it provides safe living conditions for billions of people around the world and has a significant impact on the well-being of many global economies – is unfortunately against the principles of sustainable development, generating definitely negative effects on the natural environment (Li *et al.* 2022, Garg *et al.* 2021, Golewski 2022a, e, Fakoor *et al.* 2014, 2019). The impact of the lack of ecological production of this very useful construction material concerns mainly the cement matrix of the concrete composite (Celik *et al.* 2022, Golewski and Sadowski 2006 2012, Tayeh *et al.* 2021, Ashok *et al.* 2017, Marsavina *et al.* 2017). It is mainly related to the fact that ordinary Portland cement (OPC), which is the basic binder for the production of concrete, is formed as a result of burning Portland clinker, which:

- generates significant amounts of harmful greenhouse gases, mainly CO₂, during this process (Pacheco-Torgal 2017, Golewski 2018a, b, c, d, e, Golewski and Gil 2021, Golewski and Szostak 2022, Lata and Kaur 2019a, b),
- consumes significant amounts of energy, both thermal

and electrical (Golewski 2015, Gil and Golewski 2018a, b, Haeri 2015, Haeri and Sarfarazi 2016, Zhang *et al.* 2019).

Therefore, in order to reduce the negative environmental impact of the only OPC-based concrete production, measures have been taken to reduce the share of pure Portland clinker in the composition of cements by replacing it with other mineral components in the form of additives, and recently also nanoadditives (Kaloop *et al.* 2022, Zeyad *et al.* 2019, Zhang *et al.* 2020, Oraka and Sayedi 2021, Golewski and Szostak 2021a b, Meng and Khayat 2016, Li *et al.* 2021, 2022, Abu Al-Rub 2012). More and more often, modern construction concretes are based on multi-component cements, with a more or less diversified composition, containing one or more substitutes for cement binder. Such materials are referred to as Supplementary Cementitious Materials (SCMs) (Kurtinaitiene *et al.* 2016, Szostak and Golewski 2018 2020 2021, UzzalHossain *et al.* 2018, Sokhandani *et al.* 2022). It should be emphasised that increasing the share of SCMs in OPC contributes to a significant reduction of CO₂ emissions (Golewski 2021a b) and energy consumption during the production process (Golewski 2017a, b, c, d, 2020a, 2023).

In addition, the synergistic effect of the interaction of several mineral additives has a more favourable effect on the properties of multi-component cements compared to cements containing only one mineral additive (Wu and Fang 2022, Yang and Kim 2019, Zhang *et al.* 2016, Sokhandani *et al.* 2022). This allows, among others, for

*Corresponding author, Professor,
E-mail: g.golewski@pollub.pl

preparing concrete composites resistant to significant static as well as impact, dynamic and fatigue loads (Aydogdu 2014, Golewski 2019a, b, 2020a, b, c, Madenci 2021, Lyratzakis *et al.* 2022, Park *et al.* 2021, Fakoor and Shahsavari 2021, Mehri Khansari *et al.* 2019, Xie *et al.* 2022, Rezaee *et al.* 2022). Therefore, on an increasingly larger scale, laboratory tests are carried out and then implementation works on the use of cements in concrete technology based on, for example ternary or quaternary binders (Sohu *et al.* 2022, El-Chabib and Ibrahim 2013, Biricik and Sarier 2014) are realised.

The main SCMs, used in composites based on quaternary binders, are:

- fly ash (FA) (Bhagawati *et al.* 2016),
- silica fume (SF) (Lou *et al.* 2023, Zhang *et al.* 2016),
- ground-granulated blast-furnace slag (GGBFS) (Kim and Park 2019).
- waste glass, limestone powder and crumb rubber (Ren *et al.* 2020).

More and more often, matrices of such concretes also contain nanomaterials, most often in the form of:

- nanosilica (nS) (Khater 2016),
- carbon nanotube (Li *et al.* 2021, 2022),
- active nanoseeds of C-S-H phase (Han *et al.* 2021).

Unfortunately, a significant factor inhibiting, so far, the development of concrete production based on multi-component cements is the lack of practical experience related to the use of binders of this type in concrete technology, for example in the aspects of investigation and evaluation of fracture processes in these composites (Yuan and Liao 2022, Lu *et al.* 2022).

Understanding the fracture phenomena in concretes with modified binder composition is difficult, because the large structure discontinuities occurring in such highly heterogeneous composites and the related local differences in mechanical properties of the material cause stress concentrations to an even greater extent than it can be observed in traditional cement-based concretes made on OPC. Such phenomena may cause failure of such materials to occur at stresses much lower than the allowable ones. It should also be remembered that the process of destroying the concrete element does not take place in its entire volume, but consists in the formation, accumulation and propagation of internal cracks and other material defects, which leads to the loss of internal stability, first in the Interfacial Transition Zone (ITZ) between the aggregate grains and the cement matrix, and then in the entire volume of the composite (Craciun 2008 2016, Singh *et al.* 2019, Li and Zhang 2021, Naija and Miled 2022, Trivedi *et al.* 2022, Fu *et al.* 2022).

On the other hand, plasticising effects of the material, mainly those containing additives, can be observed on the failure charts for a large group of concrete composites. Most often they result from the presence of coarse aggregate in concrete, which during the loading process detach from the cement matrix and experience slight rotations. In addition, the quasi-plastic behaviour in the loading process can also be observed in concretes containing the FA additive (Cui *et al.* 2022), or concretes subjected to high temperatures (Craciun and Soos 2006, Lou and Ma 2022).

Therefore, it was proposed to carry out considerations and then exact investigations using the non-contact measurement method (NCMM), assuming the existence of microcracks in the material. The experiments were planned for concrete composites with a modified and significantly different composition of the binder. Their aim, from the technological point of view, would be to provide information on the correctness and effectiveness of the selection of the mixture of concrete composites, in which the main cement binder would be replaced with a mixture of different SCMs. In consequence results obtained from the conducted studies would allow for the most optimal selection of the composition of the cement matrix in QBC containing both additives and nanoadditives.

Modern and very useful NCMM based on the digital image correlation system (DIC) (Abood *et al.* 2022, Sokoli *et al.* 2014) was used in order to analyze the fracture processes in QBC as accurately as possible.

It allowed for:

- detailed tracking of the development of initial cracks, developing in the structure of concrete specimens, during the loading and unloading process,
- diagnosing the level of brittleness of individual composites,
- evaluation of crack propagation processes.

Therefore, the main objective of the present study is to achieve information about the effect of simultaneous incorporation of three pozzolans as partial replacement to the OPC on the fracture processes in concretes made from quaternary binders (QBC) and based on the results to propose practical application for the examined composites.

The following article presents comprehensive analysis of the cracking in concrete composites made of binders with a highly diversified composition of the cement matrix in order to complete the literature data on the possibility of effective use of concretes based on multi-component binders. For this purpose, a composition of the two most commonly used pozzolan-active mineral additives, i.e. FA and SF in combination with a pozzolan-active nanoadditive in the form of nS, has been proposed as a partial replacement of the cement binder.

The results of the obtained measurements may turn out to be very valuable because in the case of concrete, including modified concrete, the use of modern methods and tools of fracture mechanics allows for an in-depth analysis of intra-material damage. As a consequence, it may help understand the fracture mechanisms of non-standard concrete composites, the formulation of uniform testing and design procedures as well as the reduction of the effects of fracture (Alimradzadeh and Akbas 2022, Guan *et al.* 2019 2021 2022, Zhang *et al.* 2021b).

2. Experimental section

2.1 Materials

All of the materials (excluding nS) used in the studies came from the area of Poland. Nanosilica was imported from South Korea. The constituting materials of concrete used in the present study are:

Table 1 The particle size distribution of the aggregates used

| Fraction (mm) | Content of aggregates fraction (%) | | |
|---------------|------------------------------------|--------|------|
| | Sand | Gravel | Mix |
| 0–0.125 | 2.9 | 0.7 | 1.7 |
| 0.125–0.25 | 14.8 | 0.4 | 5.6 |
| 0.25–0.5 | 41.1 | 0.4 | 15.3 |
| 0.5–1.0 | 32.7 | 1.6 | 12.4 |
| 1.0–2.0 | 4.5 | 6.9 | 5.7 |
| 2.0–4.0 | 4.0 | 19.9 | 13.9 |
| 4.0–8.0 | 0.0 | 63.1 | 40.2 |
| 8.0–16.0 | 0.0 | 7.0 | 5.2 |
| Sand point | 96.0 | 10.0 | 40.7 |

Table 2 Chemical composition of the OPC and SCMs used (mass %)

| Material/Constituent | SiO ₂ | Al ₂ O ₃ | CaO | MgO | SO ₃ | Fe ₂ O ₃ | K ₂ O | P ₂ O ₅ | TiO ₂ | Ag ₂ O |
|----------------------|------------------|--------------------------------|-------|------|-----------------|--------------------------------|------------------|-------------------------------|------------------|-------------------|
| OPC | 15.00 | 2.78 | 71.06 | 1.38 | 4.56 | 2.72 | 1.21 | - | - | - |
| Class F FA | 55.27 | 26.72 | 2.35 | 0.81 | 0.47 | 6.66 | 3.01 | 1.92 | 1.89 | 0.10 |
| Non-condensed SF | 91.90 | 0.71 | 0.31 | 1.14 | 0.45 | 2.54 | 1.53 | 0.63 | 0.01 | 0.07 |
| Konasil K-200 nS | >99.8 | - | - | - | - | - | - | - | - | - |

Table 3 Properties of binders used

| Material\Parameter | Specific gravity (g/cm ³) | Blaine's fineness (m ² /g) | Particle diameter (μm) |
|--------------------|---------------------------------------|---------------------------------------|------------------------|
| OPC | 3.11 | 0.33 | 40 |
| Class F FA | 2.14 | 0.35 | 30 |
| Non-condensed SF | 2.21 | 1.40 | 11 |
| Konasil K-200 nS | 1.10 | 200 | 0.012 |

Table 4 Concrete mix combinations used in the present investigation

| Mix | Mix No. | Weight of constituents of concrete (kg/m ³) | | | | | | | |
|--------------------------|---------|---|------|------|------|-------|----|------|--------|
| | | OPC | FA | SF | nS | Water | SP | Sand | Gravel |
| 100% OPC | Mix1 | 352 | 0 | 0 | 0 | 141 | 0 | 676 | 1205 |
| 85% OPC+0%FA+10%SF+5%nS | Mix2 | 299.2 | 0 | 35.2 | 17.6 | 141 | 6 | 676 | 1205 |
| 80% OPC+5%FA+10%SF+5%nS | Mix3 | 281.6 | 17.6 | 35.2 | 17.6 | 141 | 6 | 676 | 1205 |
| 70% OPC+15%FA+10%SF+5%nS | Mix4 | 246.4 | 52.8 | 35.2 | 17.6 | 141 | 6 | 676 | 1205 |

- OPC CEM I 32.5R from Chelm cement plant, with: the compressive strength equal to 23.3 MPa in the age of two days and 50 MPa after 28 days of curing,

- natural gravel from Las Suwalski deposit as coarse aggregates with specific gravity 2.65 and aggregate size 2.0 mm–8.0 mm,

- natural sand from Markuszów deposit as fine aggregates with specific gravity of 2.60 and maximum size of 2.0 mm.

The particle size distribution of both above aggregates is presented in Table 1.

The SCMs, which were used as partial replacement of OPC to produce QBC, are:

- class F FA, from local Puławy thermal-electric power station,
- non-condensed SF from Łaziska Ironworks,

- nS Konasil K-200 from OCI Company Ltd.

The chemical compositions and main properties of SCMs used are listed in Tables 2 and 3 respectively.

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In addition, superplasticizer (SP) STACHEMENT 2750 based on polycarboxylates (1.8% of binding material weight) was used in order to improve the flowability of the concrete. The laboratory pipeline water for preparation all mixtures was also used.

Table 5 The main mechanical parameters of investigated QBCs

| Mix No. | Mechanical property (MPa) | |
|---------|---------------------------|----------------------|
| | $f_{cm} \pm \delta$ | $f_{ctm} \pm \delta$ |
| Mix1 | 38.32±2.24 | 2.90±0.25 |
| Mix2 | 53.89±3.35 | 4.02±0.31 |
| Mix3 | 56.77±4.56 | 4.26±0.37 |
| Mix4 | 50.12±5.28 | 3.76±0.46 |

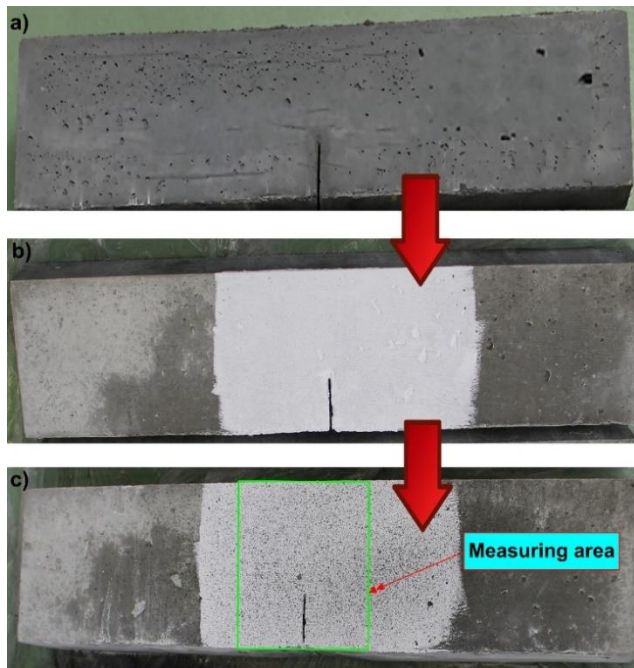


Fig. 1 Stages of specimen preparation for DIC tests: a) raw specimen, b) specimen painted with lime, c) specimen with random black speckles and measuring area

Finally, the reference concrete (Mix1) was prepared only with the use of OPC, while the other three composites (from Mix2 to Mix4) contained, in addition to OPC, SCMs in the form of: FA, SF and nS with different percentage shares. From this reason, SP was also added to each of them due to the presence of fine-grained materials in the composites based on quaternary binders.

Table 4 presents different various proportions of constituents in controlled and quaternary mixes containing: FA, SF and nS. The mix combinations incorporating SCMs were prepared by replacing: 15%, 20% and 30% of OPC by weight with these additions in quaternary mode. With the binder mixtures prepared in this way, it was possible to draw additional conclusions regarding the influence of the main SCMs, i.e. FA, the content of which in each of the 3 quaternary concretes was different (0%, 5% and 15%), on changes of the properties of composites containing highly effective pozzolanic siliceous materials, the percentage of which was constant.

The proposed selection of components for the implementation of concretes was aimed at assessing the synergy of the interaction of individual additives with each other in the direction of improving the mechanical



Fig. 2 A view of measuring area of specimen with visible black speckles

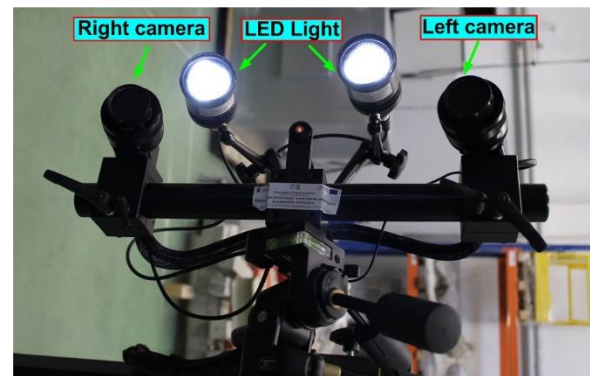


Fig. 3 The instruments of the DIC system

parameters and reducing susceptibility to cracking of composites. The control concrete (Mix1) did not contain any binder substitutes, while in the concretes based on quaternary binders, efforts were made to determine the effect of FA on the analyzed parameters of concretes containing SF and nS with a constant content of these modifiers.

For this purpose, the concrete of the Mix2 series was, in a sense, a quasi-reference concrete, i.e. with 0% FA content, in relation to materials with the OPC substitute by FA at 5% and 15% respectively in the series of concretes Mix3 and Mix4.

Moreover, Table 5 summarizes the basic mechanical parameters with standard deviations (δ), i.e. compressive strength (f_{cm}) and splitting tensile strength (f_{ctm}), which are the result of previous studies of the same composites (Golewski 2022b). The results given in Table 5, for each parameter, were obtained from the tests performed on 6 specimens (Golewski 2022b, c, d).

A total of 6 concrete beams specimens with one initial crack of size 80 x 150 x 700 mm for evaluation fracture processes in composites were casted with each batch. The preparation process for the concrete specimens is given below. It should be noted that due to the presence of nS in the composition of the concrete mix, its course was not fully standard. In the previous tests, it was observed that premixing the nanoadditive with water and SP, before putting it directly in the mixer, ensures even and complete mixing of the applied nanomaterial with the remaining components of the concrete mix (Zhang *et al.* 2021c).

Therefore, after the steps typical for the concrete mix preparation process, during which the aggregate is first

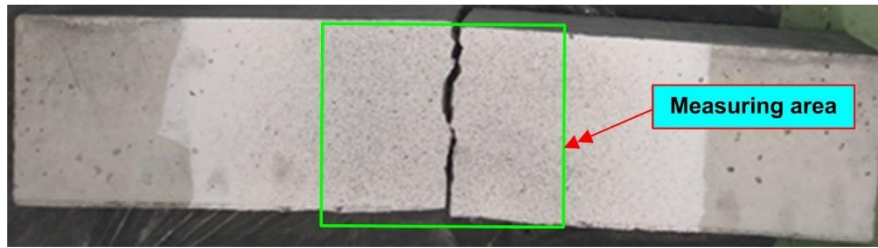


Fig. 4 A view of exemplary specimen after conducted experiments

added to the mixer and then a batch of binders containing OPC, FA and SF, the next step is to add the previously prepared mixture of nS with SP and water to the mixer. Traditionally, in the last stage the mixture is supplemented with the remaining water and the final mixing of all the ingredients starts. The total time of preparing the concrete mix is approx. 9-10 minutes. After final preparing the fresh mixture was poured into molds and compacted on a vibrating table. All the specimens were demoulded after 48 h and cured under water curing tank for the first 14 days. For the next 2 weeks, the specimens were cured in a laboratory conditions and then examined after 28 days of their preparation.

2.2 Visual analysis of fracture process

In the presented tests, the measurements of the fracture processes in QBCs were supported by the precise and useful NCMM with using DIC technique. The use of DIC capabilities also allowed for the accurate visualisation of crack propagation in the tested concretes and the diagnosis of differences in the development of damages in individual materials.

The process of specimens preparation for these tests contained the following specific steps (Fig. 1):

- at the beginning the sides of the beams, on which the deformations were to be measured, were painted with lime,
- then, after the beams dried, but before setting on a press, black dots were made on their surfaces using spray paint.

At this point it should be noted that, one of the most important elements of such procedure is placing a special pattern, i.e. speckles on the surface of the specimens, which is a reference point in the process of taking photographs by cameras. The view of the individual stages of specimen preparation for DIC tests is shown in Fig. 1. In addition, a view of measuring area of the beam for examinations of fracture processes using DIC technique, prepared based on the above activities, were presented in Fig. 2. It should be added that the speckles, visible on the surface of the beam in Figs. 1c and 2, were size from 0.1 to 1 mm.

The tests started after the stage involving the preparation of the measurement surface of the beams, which was in the immediate vicinity of the initial crack (Figures 1c, 2). Fig. 3 shows the components of the DIC system instrumentation, i.e.:

- two 5 mega pixel cameras – Baumer TXG50,
- lighting with two LED lamps.

The main basic parameters of cameras used are as follows:

- resolution: 2448x2050 pixel,

- pixel size: 3.45x3.45 μ m,

In order to trace the phenomenon of crack development in QBCs as accurately as possible, an analysis of the development stages of initial cracks in the beams was also carried out. Based on the trends observed in the process of crack initiation and propagation, which were visualized through the use of the application of the DIC technique, and on the measurement scheme presented by Zhu *et al.* (2022), the photos of the immediate area of initial cracks (Fig. 2) were analyzed at 4 levels of loading of the specimens, i.e.:

- 80% F_{max} at pre-peak stage,
- 100% F_{max} ,
- 80% F_{max} at post-peak stage,
- 20% F_{max} at post-peak stage.

Additionally, it should be noted that the influence of various types of additives and nanoadditives has a significant impact on the QBC structure. Consequently, this implies a change in the behaviour of the composite during its loading and a change in destructive processes in the material. Therefore, the following were taken into account when comparing the development of two dimensional (2D) fractures in particular concretes in the analyses:

- the stage of the initial clear appearance of a crack on the photo,
- crack length,
- the shape and morphology of the crack (straight, with curves, with branching),
- the degree of strain, observed in the photos, at which the crack propagated.

3. Results and evaluation

Fig. 4 shows a photo of one of the beams prepared of QBCs after conducted tests with clearly visible measurement surface. All the beams fractured as a result of the propagation of the damage starting at the end of the initial crack. However, during the conducted studies it was observed that the composition in the analyzed composites had a significant effect on the fracture behavior of concrete beams. The differences between the individual materials, analysed by using NCMM, were noticeable mainly in the speed of cracks propagation as well as the shape and trajectory of the macroscopic damages.

In Figs. 5 to 8 show the 2D photos taken with the use of the NCMM, supported by the DIC technique. Selected characteristic stages of fracture development, for each of the analyzed materials, were also presented on these figures. The analyses were conducted for the area of the central part of the beams with visible propagation of the initial cracks (see Fig. 1).

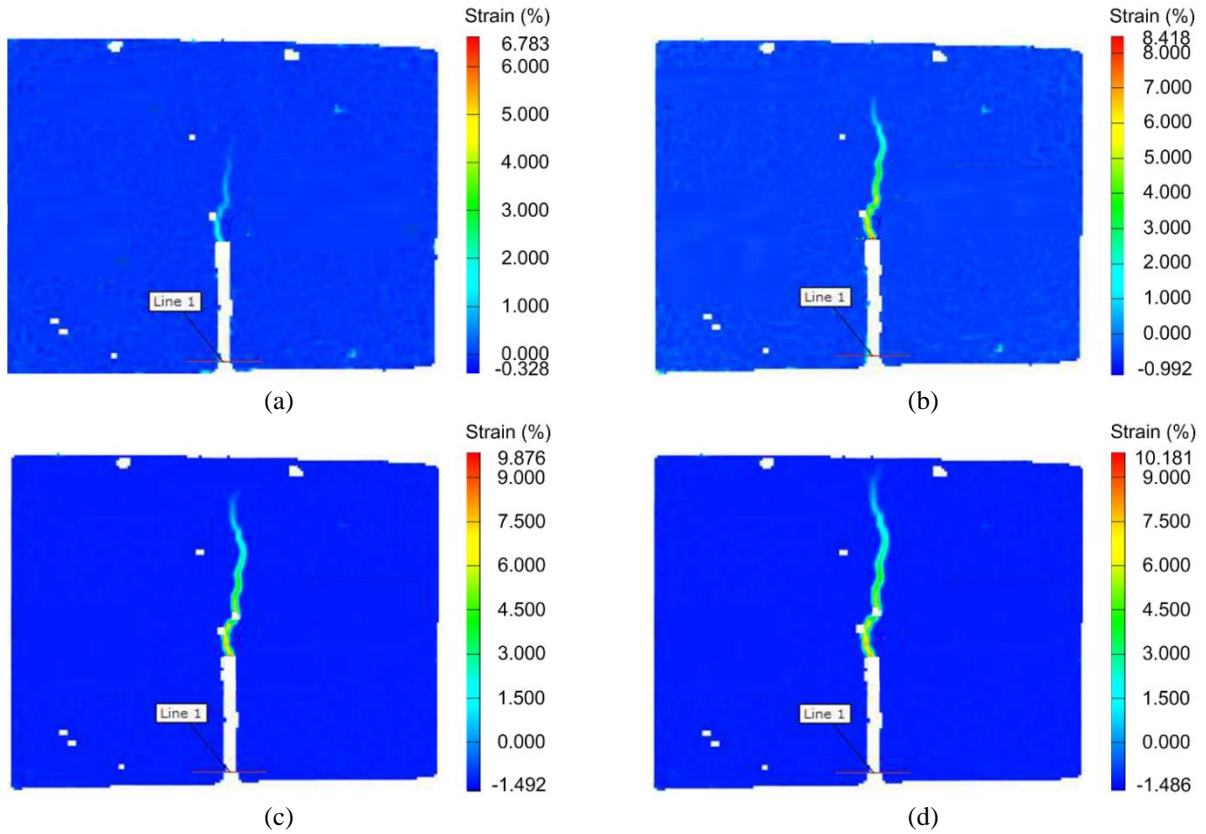


Fig. 5 Strain field for different loading stages for Mix1: a) 80% F_{max} at pre-peak stage, b) 100% F_{max} , c) 80% F_{max} at post-peak stage, : a) 20% F_{max} at post-peak stage

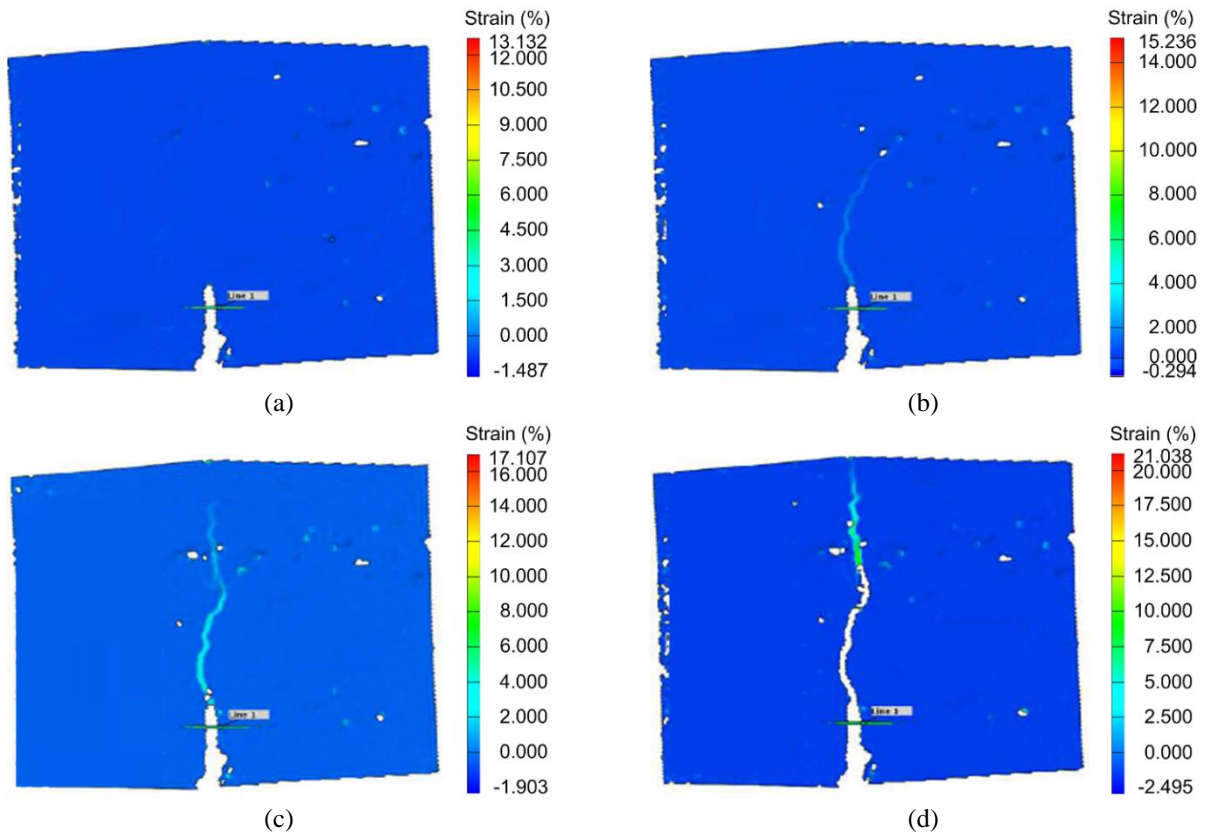


Fig. 6 Strain field for different loading stages for Mix2: a) 80% F_{max} at pre-peak stage, b) 100% F_{max} , c) 80% F_{max} at post-peak stage, : a) 20% F_{max} at post-peak stage

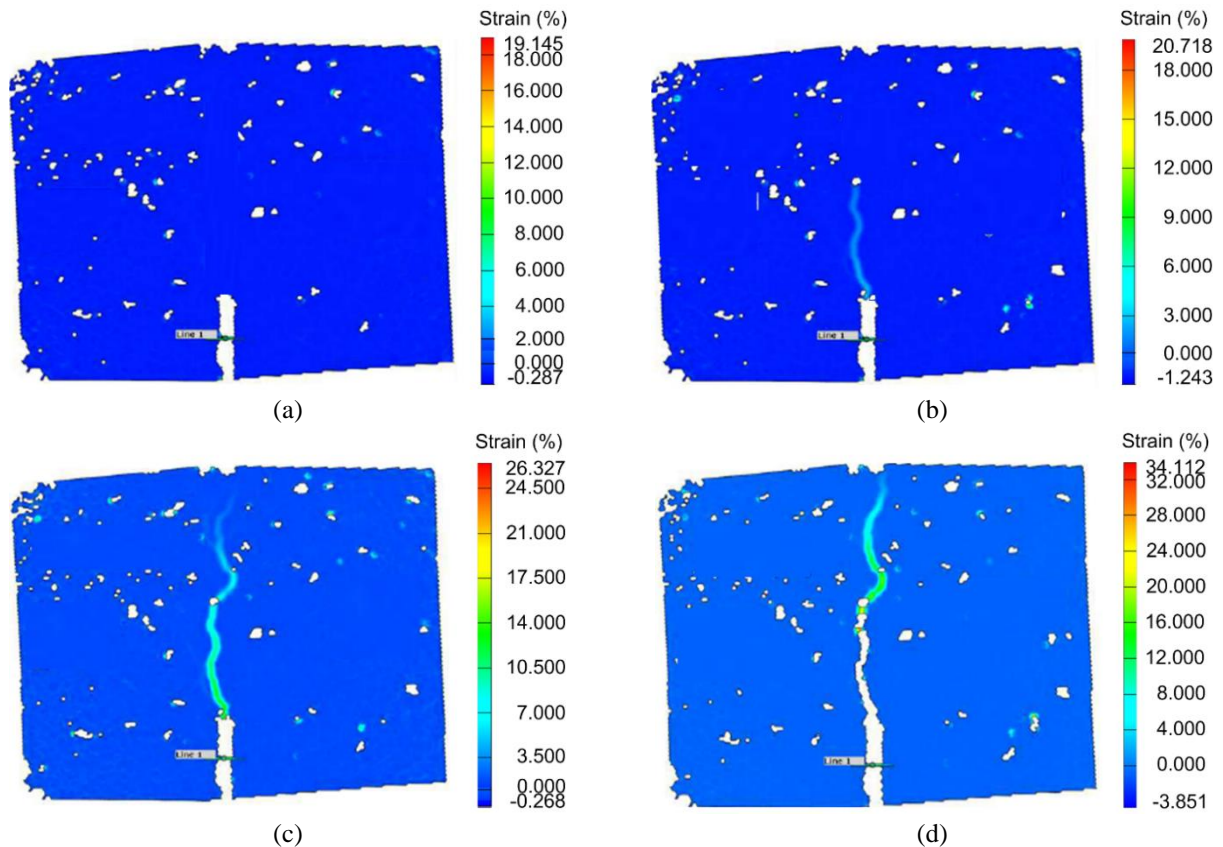


Fig. 7 Strain field for different loading stages for Mix3: a) 80% F_{max} at pre-peak stage, b) 100% F_{max} , c) 80% F_{max} at post-peak stage, : a) 20% F_{max} at post-peak stage

Table 6 Characteristics of the fracture morphology of the analyzed composites made with the addition of three pozzolans including the nanoadditive

| Mix No. | Features of the observed cracks |
|---------|--|
| Mix1 | <ul style="list-style-type: none"> • quasi-straight with visible slight curves, • visible before the occurrence of the force F_{max}. |
| Mix2 | <ul style="list-style-type: none"> • slightly curved in the first phase of the loading, but clearly rectilinear in the final phase of fracture, • visible only after the occurrence of the force F_{max}. |
| Mix3 | <ul style="list-style-type: none"> • curved along the entire height, • invisible before the occurrence of force F_{max}. |
| Mix4 | <ul style="list-style-type: none"> • full height curved along the entire height with branches, • visible before the occurrence of force F_{max}. |

In the case of beams made of unmodified concrete, i.e. Mix1 (Fig. 5), the first cracks appeared in the material at the lowest strain level observed – 6.783%, even before the occurrence of forces F_{max} . The cracks propagated stably, with a clearly rectilinear shape, at the subsequent stages of loading. The strain increment in this material, from the first measurement level to the stage shortly before destruction – 10.181%, amounted to less than 4% (Fig. 5).

The crack development, which leads to the failure of the specimen made of unmodified concrete, was therefore stable. The observed shape of the crack indicated that it develops in homogeneous concrete. The crack path shown in Fig. 5 did not reveal excessive number of its strain intervals.

In the case of concrete of series Mix2 (Fig. 6), no

significant damage was observed before the occurrence of the force F_{max} . The shape of the propagating crack in this material, although initially it had a tendency to curve, was clearly rectilinear at the final stages of the specimen loading.

In concrete Mix2, which was the most brittle of all composites, the strain level at crack initiation was only slightly lower than in the case of the composite of series Mix3 – 15.236%. Nevertheless, its range to the value shortly before failure – 21.038%, amounted only to approx. 6% (Fig. 8).

Also in the case of concrete of series Mix3, the first cracks diagnosed by the NCMM were visible only at the second measurement stage, i.e. at 100% of value of the acting load (Fig. 7). At this point, the crack was still slightly marked,

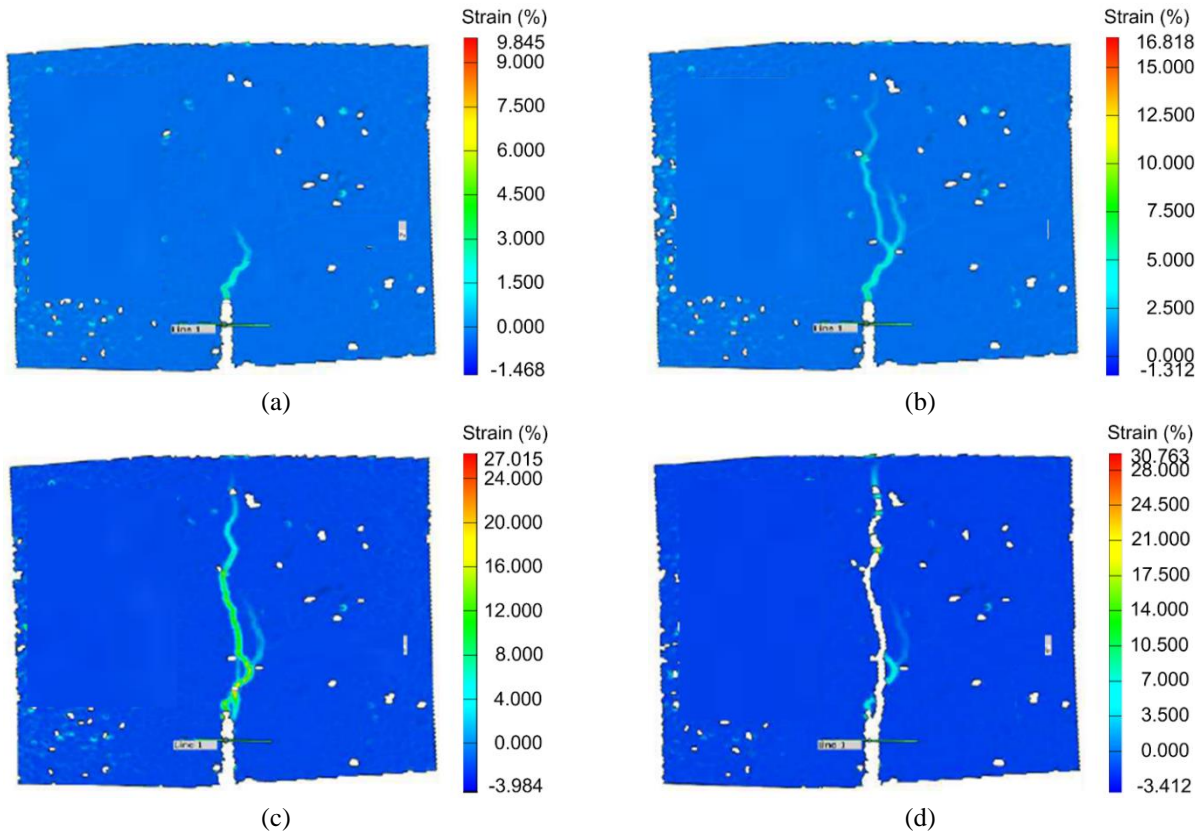


Fig. 8 Strain field for different loading stages for Mix4: a) 80% F_{max} at pre-peak stage, b) 100% F_{max} , c) 80% F_{max} at post-peak stage, : a) 20% F_{max} at post-peak stage

yet it had a distinct tendency to curve. Its target shape was confirmed by subsequent photos, which clearly show the curvilinear character of the fracture.

In addition, the level of strain in this material, quite high at the time of failure - 20.718%, increased to the stage before failure up to 34.112% (Fig. 7). This proves that the fracture propagation process lasted for a long time and its development was stable with the signs of quasi-plastic fracture. This is confirmed by the shape of the observed crack shown in Fig. 7d. In QBC with a higher content of FA, i.e. Mix4, the beginning of the significant cracking of the material was visible even before the peak load (Fig. 8). It was therefore a similar behavior of the material as in the case of unmodified concrete (Fig. 5a). The crack was curved in the initial stage of development and its image had clear branching in the subsequent stages of the load. This proves the high heterogeneity of this material (Fig. 8).

The strain level at the fracture initiation - 9.845%, was clearly lower than in the case of the previously discussed composites. In addition, the strain range up to the last stage, where the values of the order of 30.763% were read, was much longer than it was in the concretes of series Mix 2 and Mix3 (Fig.s 6b, 7b).

4. Discussion

When analyzing the moment of initiation of the first cracks, which occurred inside the material structure, as well as their shape and propagation trajectories – obtained with the use of modern NCM based on the DIC technique – it

should be stated that:

- in the case of concrete prepared by using only OPC, i.e. for Mix1 series, the cracks propagated stably, with a clearly rectilinear shape or sometimes with slight curves, the first cracks were visible before the occurrence of the force F_{max} (Fig. 5),

- for Mix2 series, delayed initiation of initial fractures and brittle behaviour of the material during the process of its damage were observed, the cracks in this composite were visible after the occurrence of the force F_{max} and their were slightly curved in the first phase of the loading, but clearly rectilinear in the final phase of fracture (Fig. 6), It should be noted that, similar brittle behavior of ordinary and high performance concretes containing SF and nS was also confirmed by other authors, e.g. (Tasdemir *et al.* 1996, Smarzewski 2019, Zhang *et al.* 2021a), Moreover, based on the research results presented by Lam *et al.* (1998) the fracture behaviors of silica fume concrete are more brittle than plain concrete and the brittleness index of these composites increased significantly (Tasdemir *et al.* 1996, Zhang *et al.* 2016). On the other hand, typical brittle failure pattern was reached in concretes incorporating nS (Rahim *et al.* 2022).

- for Mix3 series, delayed initiation of initial fractures and quasi-plastic behaviour of the material in the fracture propagation process were observed, the cracks in this composite were visible after the occurrence of the force F_{max} and their were curved along the entire height (Fig. 7),

- for Mix4 series, the beginning of the initiation of the initial fractures at the moment of peak load in the specimens

and the strictly quasi-plastic fracture of the material were diagnosed, the cracks in this composite were visible before the occurrence of the force F_{\max} and their were curved with branches along the entire height (Fig. 8),

On the basis of the analyses of the fracture processes occurring in the QBCs, prepared by using three pozzolans including the nanoadditive in the form of nS, Table 6 summarises the significant properties of the tested materials in terms of their susceptibility to cracking. The compilation focuses on the comparison of concrete behaviour in the process of their cyclic loading and unloading as well as characteristics of the fracture initiation and propagation process.

5. Conclusions

This study presents results of deep investigations of fracture processes of cementitious composites incorporating three different pozzolanic active mineral additives. In addition to the standard SCMs (in the form of FA and SF) in the structure of the analyzed concretes, the additive of very active nanopozzolan, in the form of nS, was also used. From the presented studies the following conclusions can be drawn:

- The substitution of OPC with three pozzolans including the nanoadditive in FA+SF+nS combination causes a clear change of brittleness and behavior during fractures in QBCs.
- The total addition of siliceous materials without FA, in the Mix2, increases the brittleness of such composites (Fig. 6).
- Supplementing the composition of the binder with SF and Ns with the 5% FA additive, in the Mix3, causes a slight change in the behaviour of the material in the process of its destruction from clearly brittle to quasi-plastic (Fig. 7).
- An increase in the FA content in the concrete mix by another 10% causes a significant change in fracture process in this composite in comparison to concrete with the addition of silica modifiers only. In concrete of series Mix4 the quasi-plastic fracture is already clearly visible (Fig. 8).
- The shape of cracks in unmodified concrete was quasi-linear (Fig. 5). Substitution of the binder by SCMs resulted in a slight heterogeneity of the structure of the Mix2 concrete and clear heterogeneity for concretes with the FA additive. It was the most clearly visible in the crack propagation process in Mix4 concrete, which were clearly curved and had branching (Fig. 8). In the case of concrete with a lower content of FA, the cracks were curved along the entire height of the specimens and throughout the entire development process (Fig. 7), while in the concrete of series Mix2 – slight curvature of the cracks were visible only in the first stage of their development (Fig. 6).

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